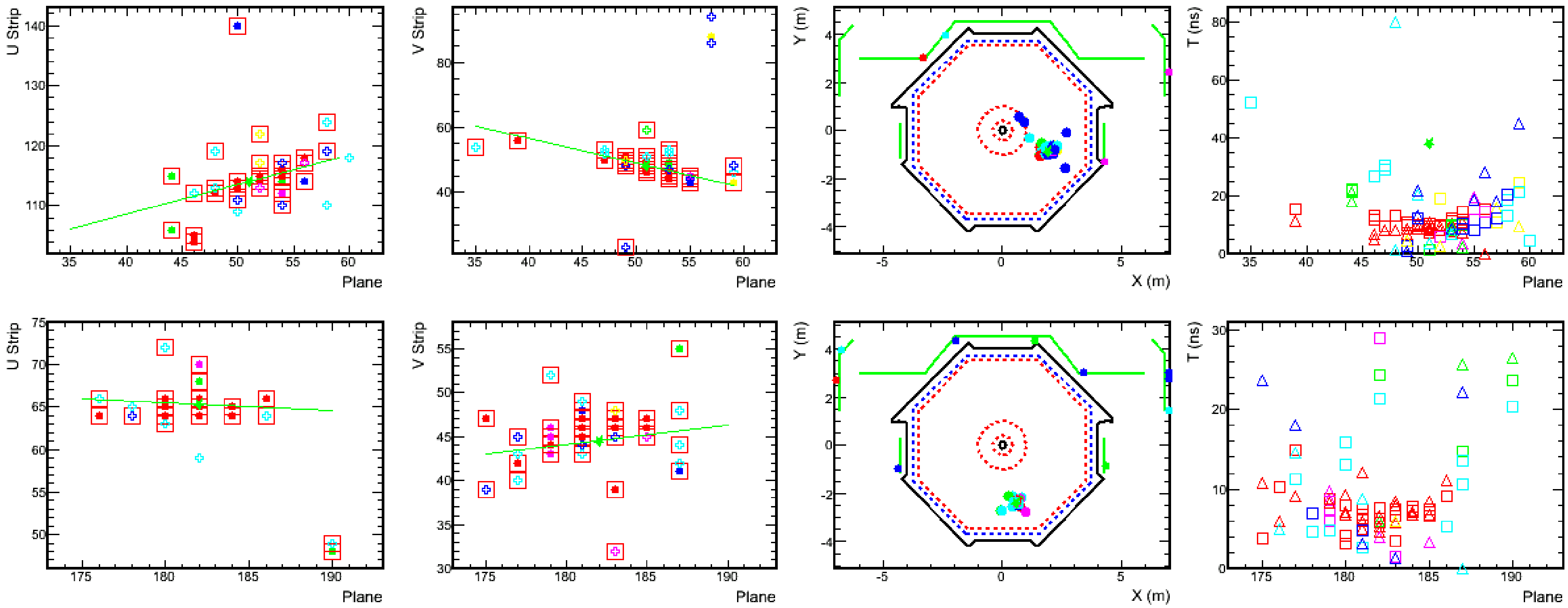
Atmospheric Electron Neutrinos in the MINOS Far Detector



Ben Speakman, Unversity of Minnesota

Week in the Wood Thesis Talk

June 15, 2007

Talk Outline

- Analysis Motivation
- Showering Event Selection
- Track-like Event Selection
- Cosmic-Ray Veto Shield
- Double Ratio Measurement
- Neutrino Oscillation Analysis
- Atmospheric Neutrino Flux Measurement

Analysis Motivation & Strategy

- Isolate contained vertex (CV) atmospheric ν_e CC + ν NC rich "Showering" events and ν_μ CC rich "Track-like" events.
- Evaluate oscillation with the flavor double ratio

$$R = (\#\ \text{Trk}/\#\ \text{Shw})_{\text{Data/MC}} \sim (\nu_\mu\ /\ \nu_e)_{\text{Data/MC}}$$

- Measure the atmospheric neutrino flux with the combination of #Trk and #Shw.
- Use Cambridge ntuple set from construction completion (8/2003) until beam running (2/2005), total of 418.5 live days.

Atmospheric ν Selection and Cosmic Ray Reduction

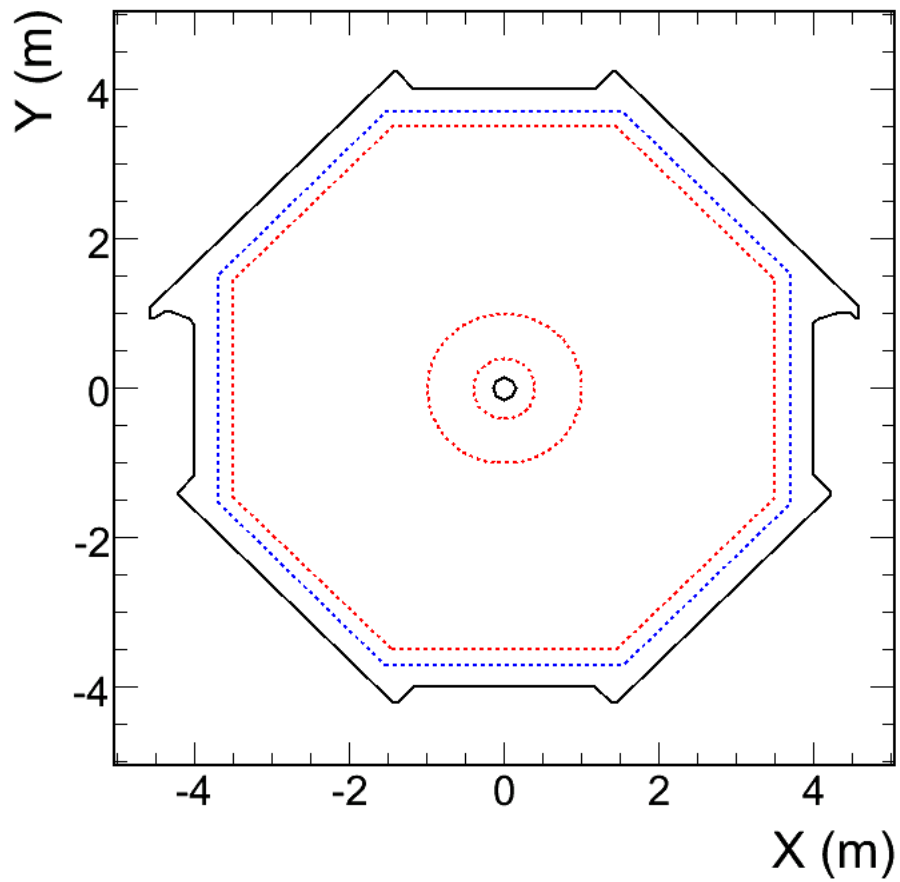
<u>How does one go about reducing the cosmic-ray background?</u>

1. Bury the detector, ½ mile should do it.
2. Select "contained vertex" (CV) events.
3. Remove steep and shallow events.
4. Observe ν-like event topologies.
5. Use the cosmic-ray veto shield.

Energy and Vertex Containment

- Energy Containment low-level filter
  - 3-D Hit Positions
  - 30 cm to Outer Edge
  - 5 Planes to SM Edge
  - Defines events as PC, FC, or through-going
- Vertex Containment event-level filter
  - Shower/Track Vertex
  - 50 cm to Outer Edge
  - 5 Planes to SM Edge
  - 40 cm from Center, or 100cm from Center on outer planes

Fiducial Mass = 3.94 kton



CV Event Selection Strategy

Showering Events

1. 1 Shower (≥ 5 Planes)
2. Clean Event & Shower
3. Shower Length Cut Optimization
   Short Shower ≤ 8 Planes
   Long Shower > 8 Planes
4. Trace Z Selection
5. Shower Topology
   a. Principal Axes Moments
   b. Energy Deposition Profile
6. Veto Shield Tagging

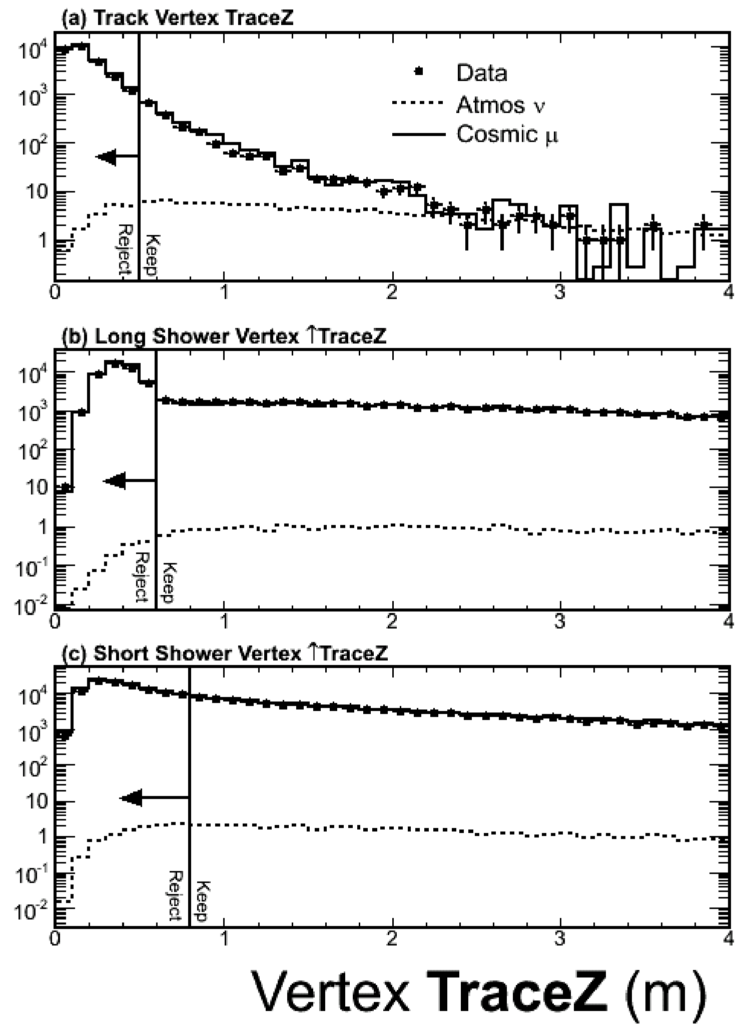
Track-like Events

Based on Cambridge Selection

1. 1 Track (≥ 8 Planes)
2. Clean Event & Track
3. FC & PC Down Tracks
   a. Trace Z Selection
   b. Vertex Hits Topology
   c. Veto Shield Tagging
4. PC Up Tracks
   a. Timing Quality

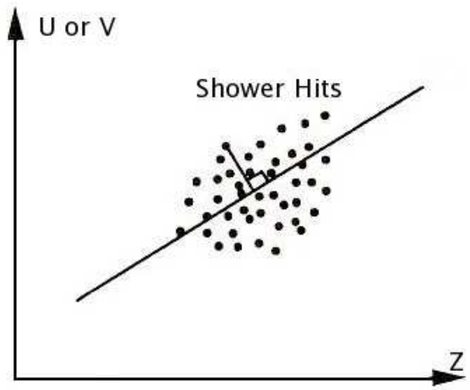
TraceZ Enhanced Containment

- **Trace** the distance back the nearest edge.
- Project **Trace** on to the Z-axis $\rightarrow$ **TraceZ**
- Tracks: **TraceZ** > 50 cm
- Showers: Use $\uparrow$**TraceZ**
  - **$\uparrow$TraceZ > 60 cm (Long Shw)**
  - **$\uparrow$TraceZ > 80 cm (Short Shw)**



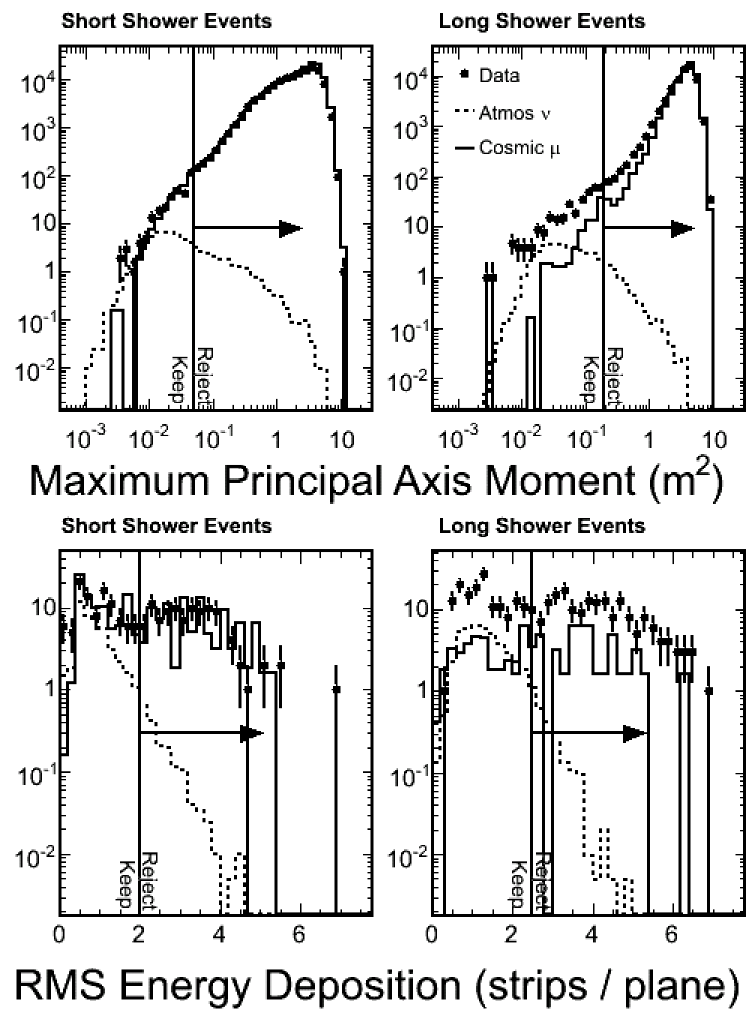
Shower Topology Selection

- Moment about Principal Axis



- Shower Energy Deposition Profile
  - Shower energy deposition in a plane ~ number of strips

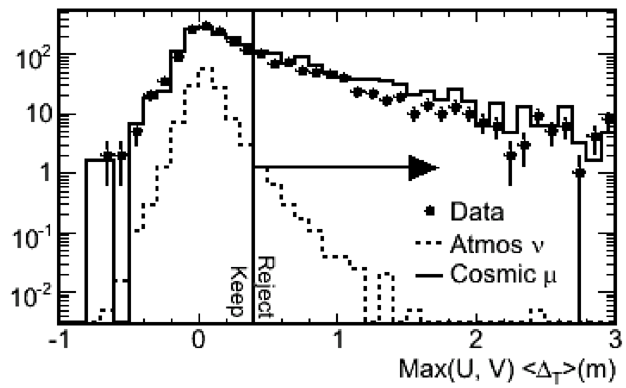
RMSStpPln = <(strips/plane)^2>^{½}

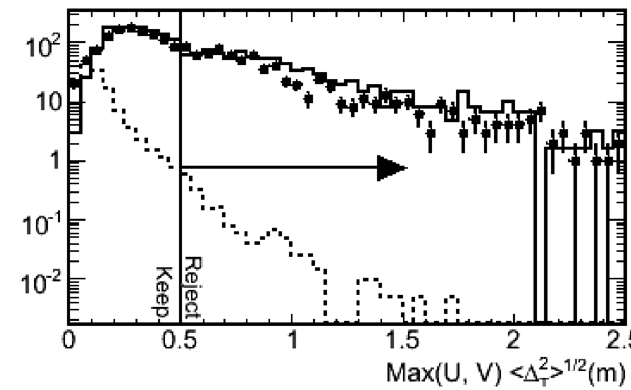


FC / PCDN Track Topology Selection

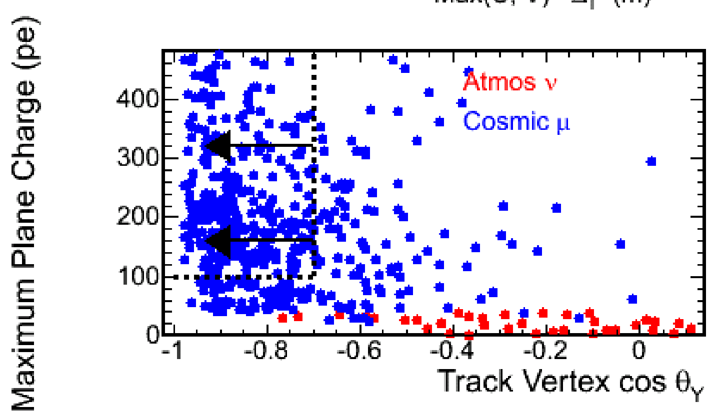
Topology of hits in vertex planes are examined for two pathologies.

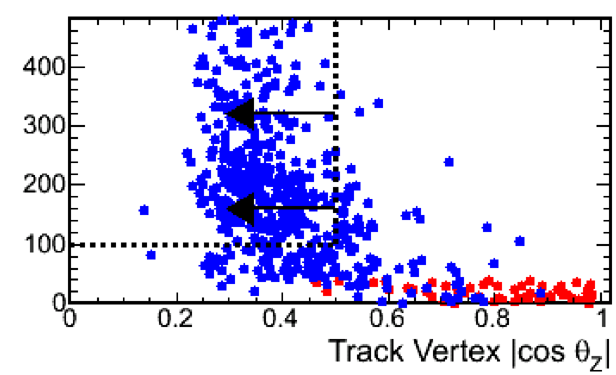
1. ΔT = Distance from vertex in each view, use mean and RMS.





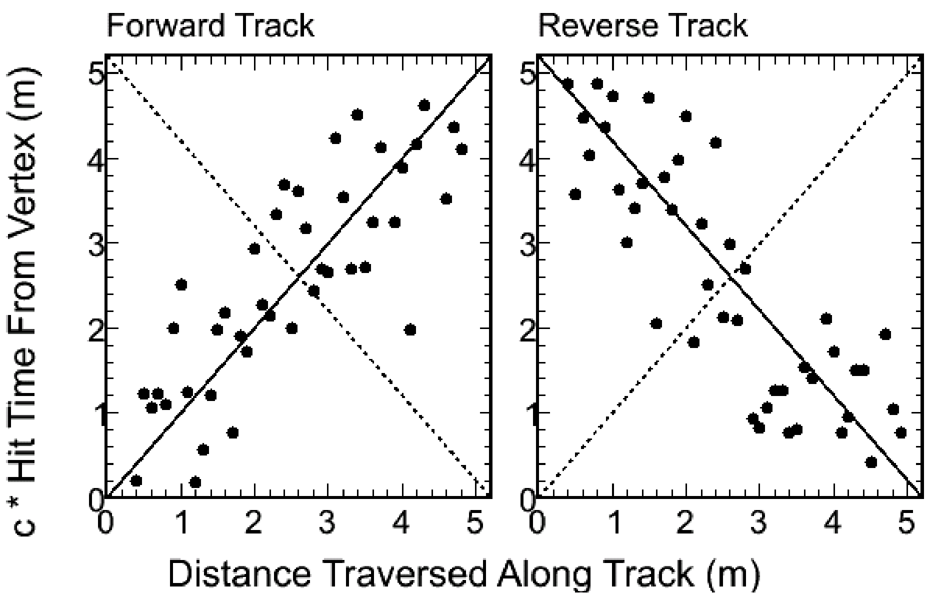
2. Q_{Max} = Maximum Vertex Plane Charge, for steep events



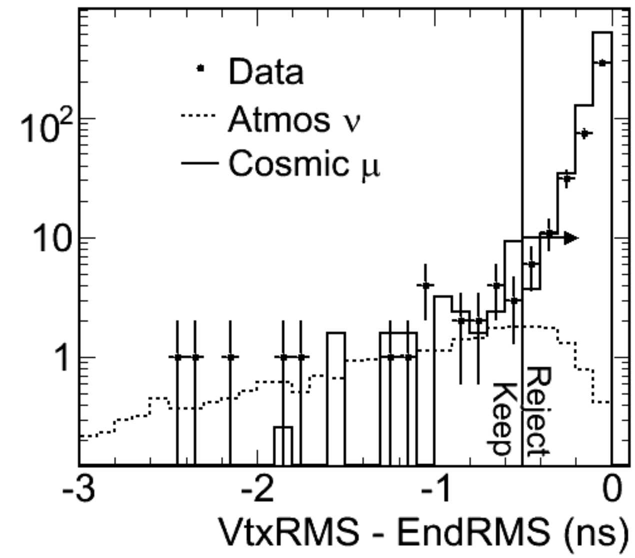


PCUP Track Timing Selection

- Track direction is decided with timing fit



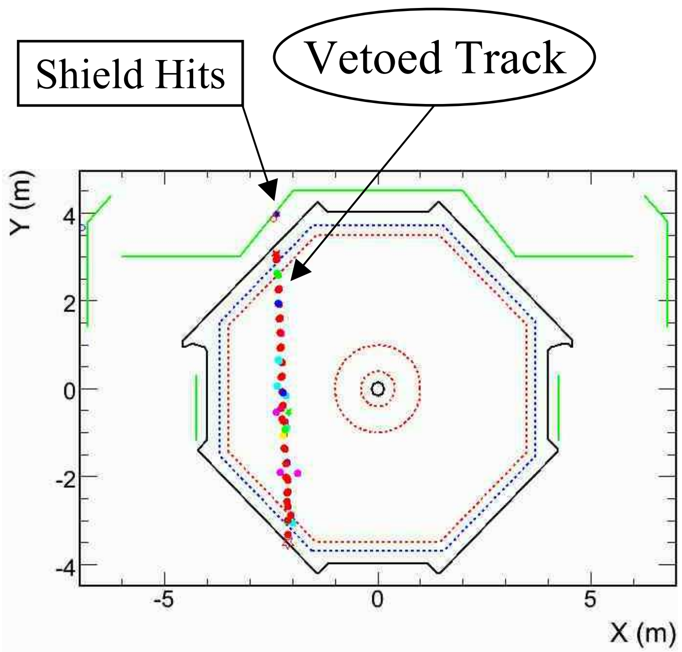
- One direction fits better, and track sides labeled “vertex” and “end”



- Quality of Upward vs Downward Fit verifies direction

Veto Shield Tagging

- Coincident hits in the shield will tag Shower or FC/PCDN Track as vetoed.



- Tagging Efficiencies
  - Cosmic-ray eff. (ε)
  - Atmos ν eff (η)
- Data used to measure Efficiencies.

D (data) = S (Signal) + V(Vetoed)

$$D = N_\nu + N_\mu$$

$$V = \eta \times N_\nu + \varepsilon \times N_\mu$$

$$S = (1-\eta) \times N_\nu + (1-\varepsilon) \times N_\mu$$

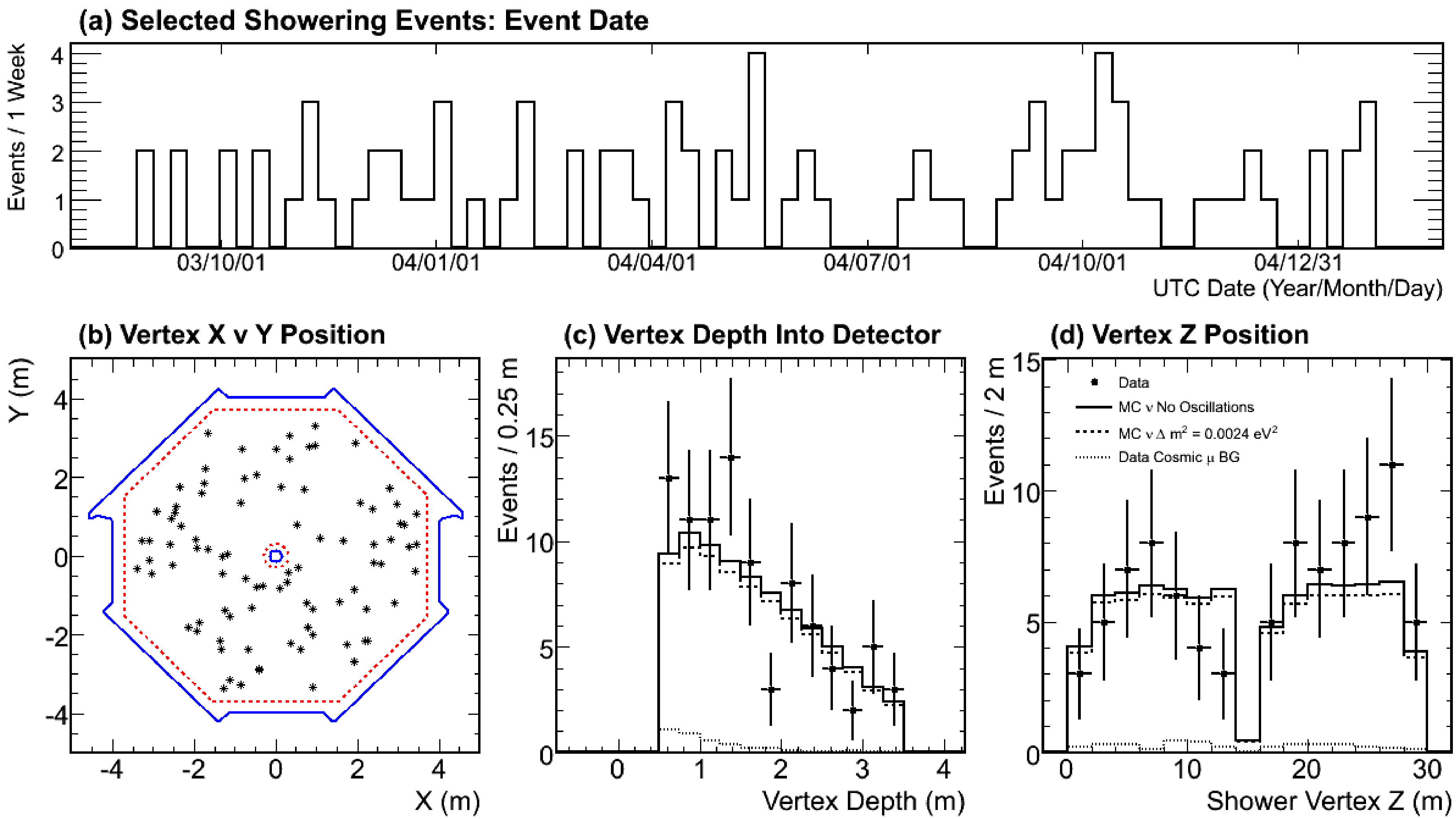
Shower Selection Results

Cut	Data	MC Expectation ν_e CC	ν_μ CC	ν NC	CR μ	N
Pre-selection	**792800**	101.4±0.7	66.8±0.6	34.0±0.4	**885072±1233**	**68.0±3.3**
Shower Quality	**345662**	67.9	40.7	22.1	**401330**	**26.5**
Vertex TraceZ	**196934**	64.3	34.6	20.6	**223562**	**19.0**
Principal Moment	**533**	53.4	19.9	15.7	**223**	**2.6**
Energy Profile	**251**	**50.4**	**19.0**	**15.0**	**126**	**2.4**
Shield	**89**	**81.8 ± 0.6**			**3.81±0.58**	**2.3±0.6**

$\varepsilon_{shw} = 0.976 \pm 0.002$
$\eta_{shw} = 0.0261 \pm 0.0011$

Scale MC ν, N by $(\varepsilon - \eta)/\varepsilon$ to match shield
Scale Vetoed by $(1-\eta)/\varepsilon$ to measure CR μ

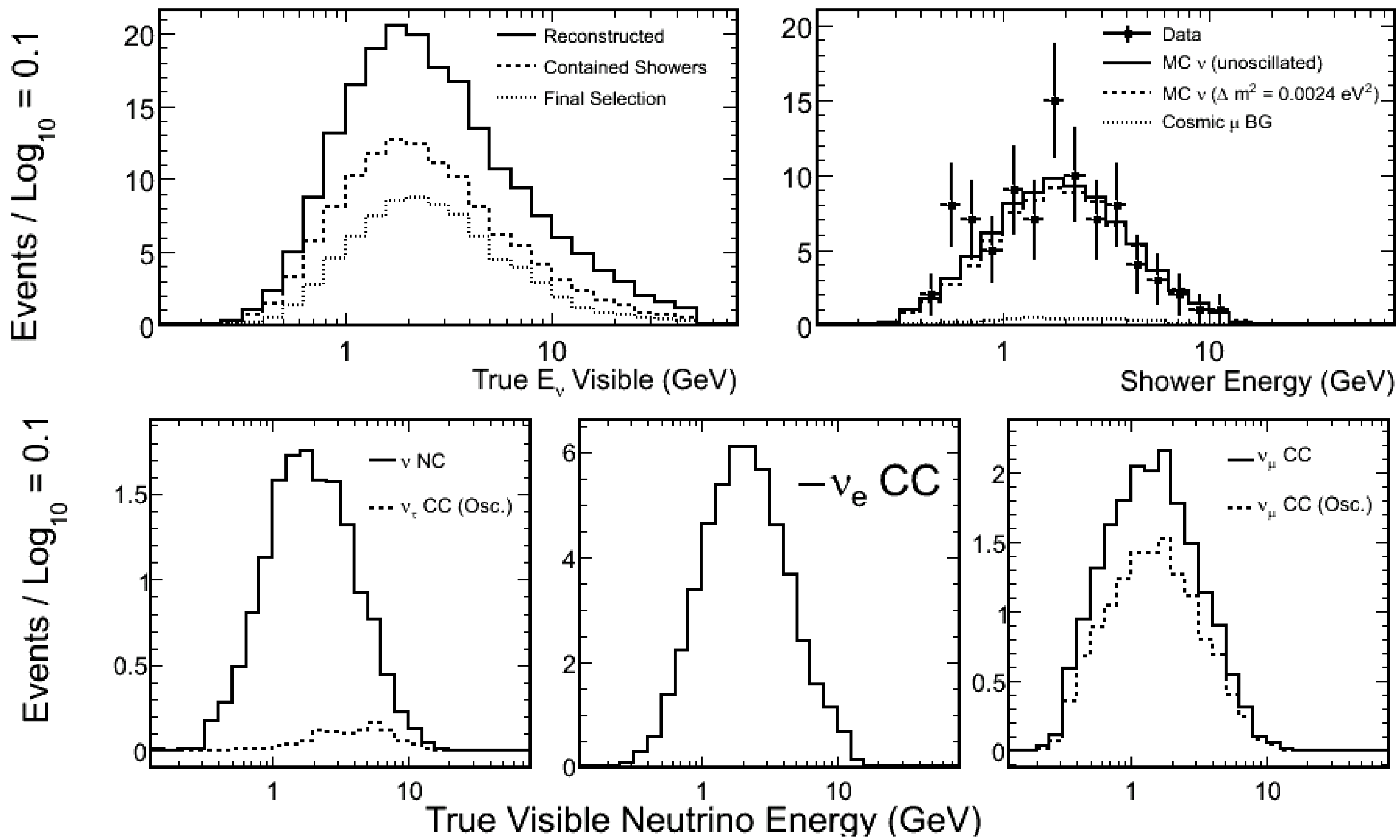
Selected Shower Events



Shower Spectra

Shower energy tuned to ν_e CC

$$\frac{\sigma_E}{E} = 20\% \otimes \frac{45\%}{\sqrt{E}}$$



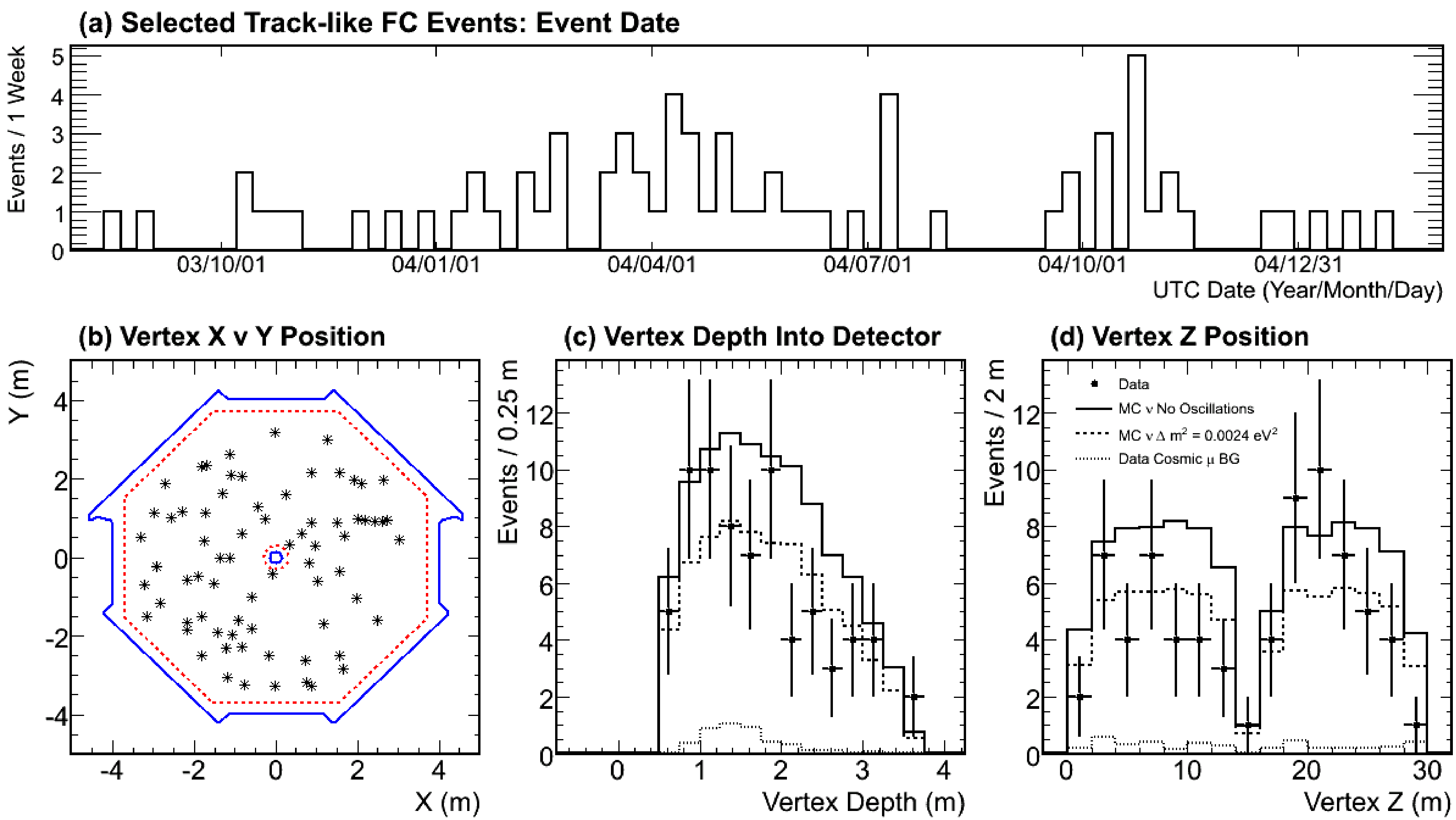
FC / PCDN Track Selection Results

Cut	Data	MC Expectation ν_μ CC	ν_e CC	ν NC	CR μ	N
Pre-selection	**54072**	186.7±1.0	10.8±0.2	7.6±0.2	**58496±260**	**4.0±0.8**
Track Quality	**30656**	143.1	3.9	3.2	**34721**	**1.6**
Vertex TraceZ	**1926**	127.7	3.5	3.0	**2284**	**0**
Vertex Hits	**1025**	124.1	3.4	2.8	**1099**	**0**
Vertex Charge	**293**	**118.9**	**3.3**	**2.7**	**215.7**	**0**
Shield	**97**	**121.6 ± 0.8**			**5.2 ± 0.8**	**<0.03**

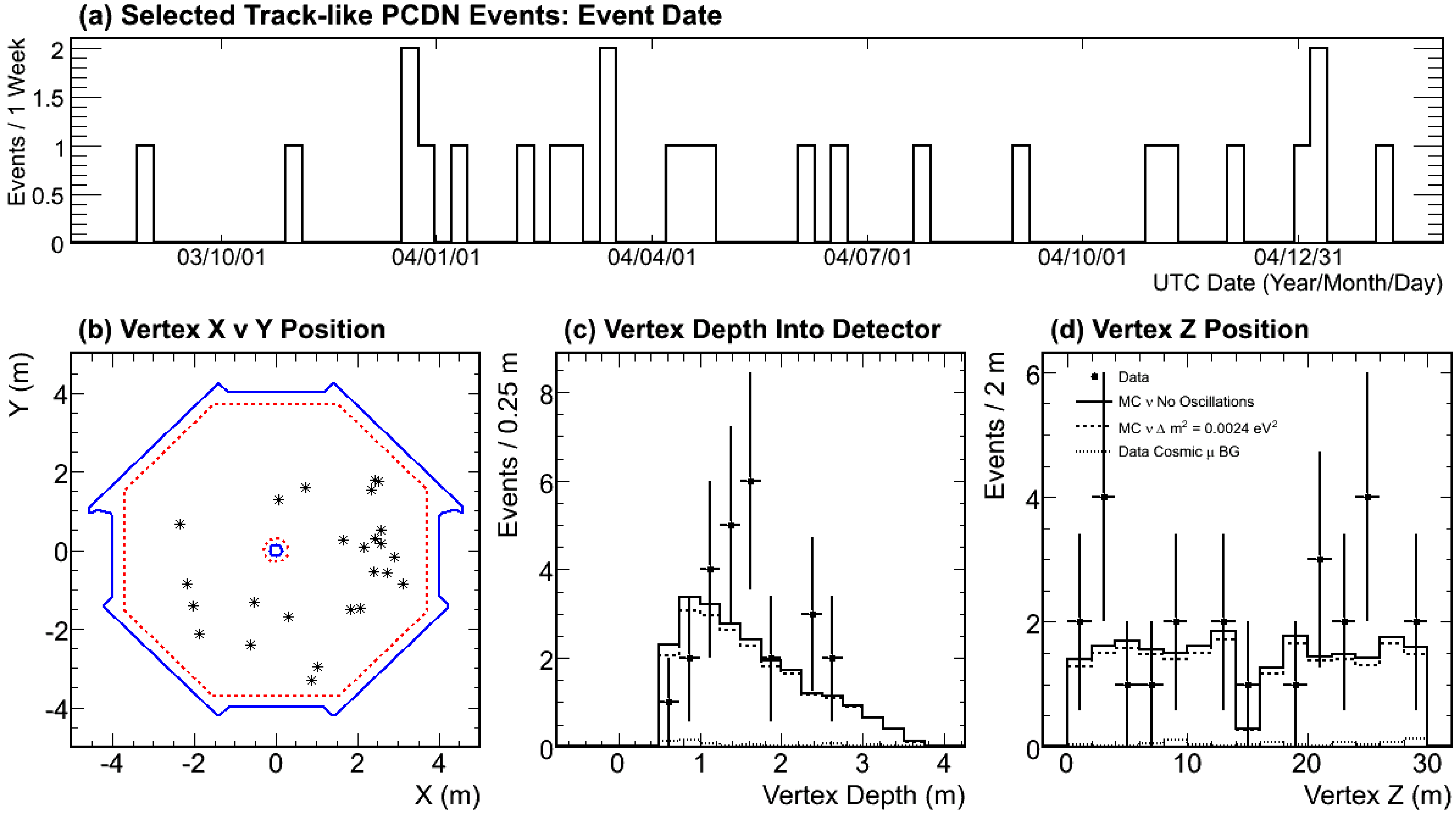
$\varepsilon_{trk} = 0.973 \pm 0.004$
$\eta_{trk} = 0.0255 \pm 0.0011$

Scale MC ν, N by $(\varepsilon - \eta)/\varepsilon$ to match shield
Scale Vetoed by $(1-\eta)/\varepsilon$ to measure CR μ

Selected FC Track Events

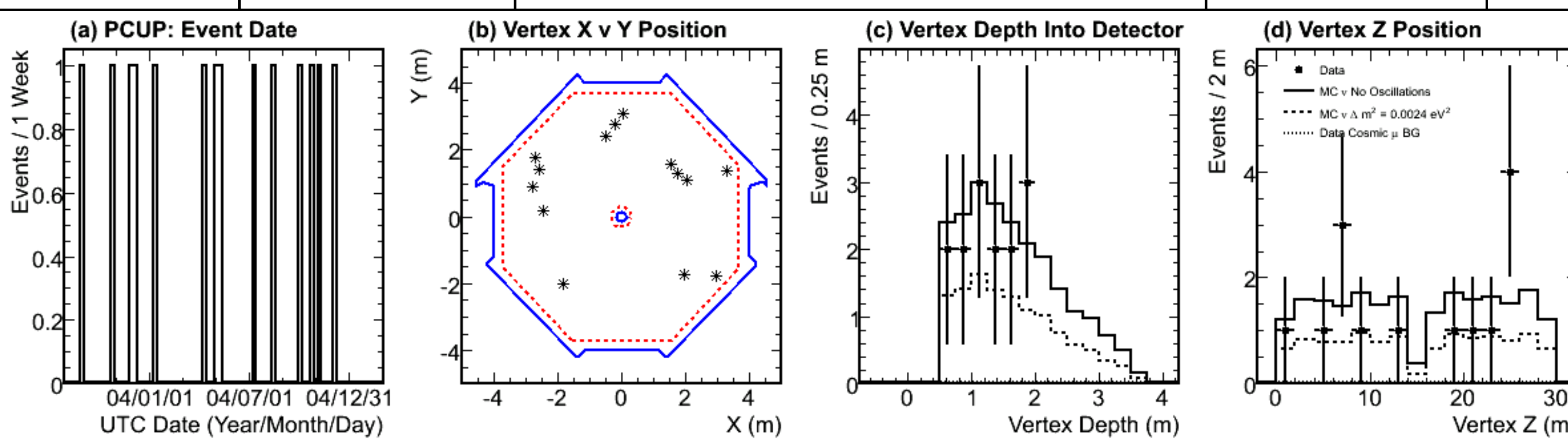


Selected PCDN Track Events



PCUP Track Selection

		MC Expectation				
Cut	Data	ν_μ CC	ν_e CC	ν NC	CR μ	N
Pre-selection	**2999**	35.0±0.4	0.51±0.05	0.43±0.05	**3493±64**	**1.6±0.5**
Track Quality	**391**	26.8	0.069	0.088	**616**	**0**
Timing Quality	**14**	**21.1**	**0.020**	**0.024**	**0**	**0**
Final Count	**14**	**21.7±0.3**			**<0.41**	**<0.04**



Atmospheric Neutrino Flavor Double Ratio

- Double Ratio = (# Tracks/# Showers)$_{(Data/MC)}$
- Observe 89 Showers and 112 Tracks
- Use the shield efficiencies to adjust FC/PCDN Track and Shower expectations.
- ExpShw = 88.8 ± 0.9 (MC Statistical)
- ExpTrk = 149.8 ± 0.9

$$\mathbf{R} = 0.746^{+0.116}_{-0.099}\text{(statistical)}$$

- Coverages found with Monte Carlo, also find that observed disfavours null oscillation hypothesis to 98.7% single-sided confidence limit.

Double Ratio Systematic Errors

Use the following systematic variances to observe:
Δ(# Tracks), Δ(# Showers), and $\Delta\mathbf{R}$

1. Tracking Energy Cutoff: 100keV vs.10keV
2. Neutrino Flux Normalization: ±20%
3. Quasi-Elastic cross-section: ±10%
4. Neutral-Current cross-section: ±25%
5. Neutron Flux Normalization: ±20%

Double Ratio Systematic Errors

	ΔE_{shw}(%)	Δ E_{trk}(%)	Δ R(%)
10keV Cutoff	+4.26	+0.023	+4.24
ν **Flux ±20%**	±18.5	±19.3	±0.742
NC ±25%	±4.11	±0.453	±3.64
QE ±10%	±2.62	±4.43	-(±1.72)
Neutron ±20%	±0.533	±0.0	±0.529

Cumulative Systematic Error Δ**R**= 5.93%

$$\mathbf{R} = 0.746^{+0.116}_{-0.099}(\text{stat.}) \pm 0.044(\text{syst.})$$

Double Ratio Results

$$\mathbf{R} = 0.746^{+0.116}_{-0.099}(\text{stat.}) \pm 0.044(\text{syst.})$$

Statistically disfavors null oscillation at 97.3%

Accounting for systematic error,
disfavors null oscillation at 96.0%

Atmospheric Neutrino Flux Measurement

- Flux measurement is expressed as a normalization factor (S_{atm}) to a particular flux model.
- First order calculation, use the number of showering neutrino interactions with the *Bartol04-3D* atmospheric neutrino model.

$$S_{atm} = 1.01 \pm 0.12 \pm 0.07$$

- Flux measurement can be enhanced with an oscillation analysis.

Maximum Likelihood Method

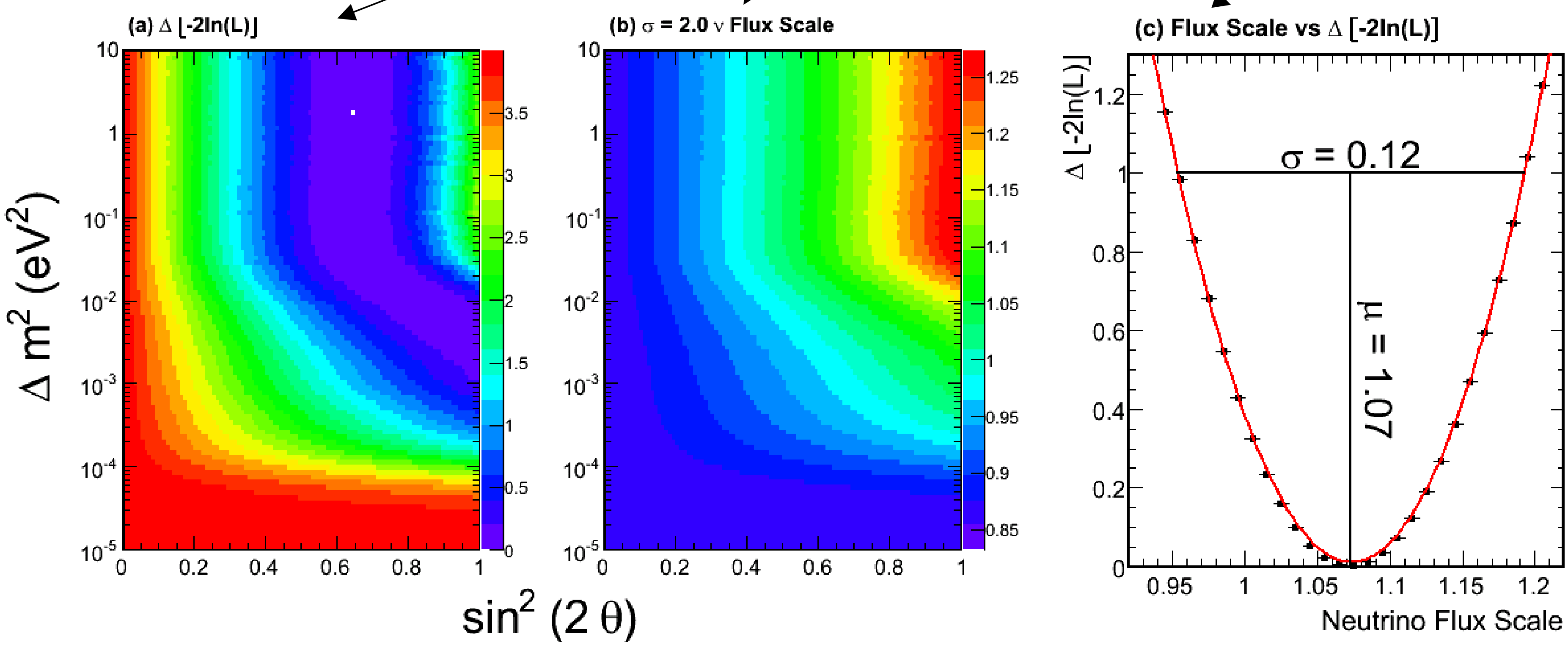
- Minimize the negative-log likelihood.

  $$-2\ln[\mathcal{L}] = 2\Sigma[E_i - O_i * \ln(E_i)] + (\alpha/\sigma)^2$$

- Fit three parameters (S_{atm}, $\sin^2(2\theta)$, Δm^2) to two bins (# of showers and tracks)
- Penalize the scale factor: $\alpha = S_{atm} - 1.0$
- Use $\sigma = 2.0$ to penalize weakly, permitting the flux normalization to float freely and account for oscillation

Weakly Penalized Scale Factor

Combine Δ [–2 ln (L)]
With Best Fit S_{atm}
To measure S_{atm}



Flux Scale Result

	Adjusted S_{atm}	$\Delta S_{atm}(\%)$
10keV Cutoff	1.02	-4.88
NC ±25%	1.02, 1.13	-5.20, +5.78
QE ±10%	1.05, 1.10	-2.51, +2.62
Neutron ±20%	1.07, 1.08	-0.676, +0.673

Cumulative Systematic Error = 8.92%

$S_{atm} = 1.07 \pm 0.12(\text{stat.}) \pm 0.09(\text{syst.})$

Model Gives $S_{atm} = 1.0 \pm 0.2$

Comparison to Soudan2 Flux Measurement

- Soudan2 measurements of Flux from ***Bartol04-3D*** Model

$$S_{atm}(\text{no-osc}) = 0.88 \pm 0.07$$

$$S_{atm}(\text{osc}) = 0.91 \pm 0.07$$

- Compared to the MINOS measurement

$$S_{atm}(\text{no-osc}) = 1.01 \pm 0.12 \pm 0.08$$

$$S_{atm}(\text{osc}) = 1.07 \pm 0.12 \pm 0.09$$

Summary Analysis Results

- Double Ratio

$$\mathbf{R} = 0.746\,^{+0.116}_{-0.099}\,(\text{stat.}) \pm 0.044\,(\text{syst.})$$

96.0% Rejection of Null Oscillation

Compare to Super-K (45kty) $R = 0.68 \pm 0.03 \pm 0.05$

- ***Bartol04-3D*** Flux Model Normalizaton

$$S_{atm} = 1.07 \pm 0.12(\text{stat.}) \pm 0.09(\text{syst.})$$

Compare to model prediction $S_{atm} = 1.0 \pm 0.2$

and Soudan2 $S_{atm} = 0.91 \pm 0.07$

Conclusion

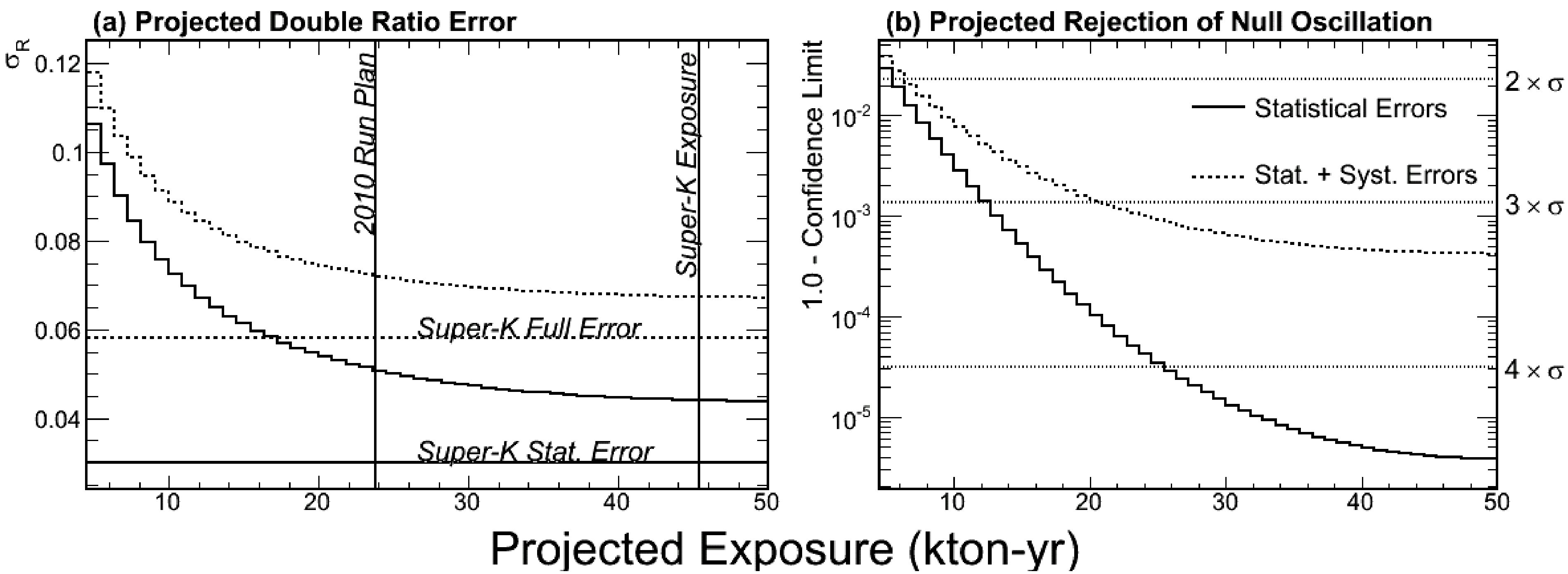
- Atmospheric flavor double ratio suggests neutrino oscillation, disfavors null oscillation with reasonable confidence.
- Understanding of the atmospheric neutrino flux model can be, and has been improved with the measurement of a normalization factor to the ***Bartol04-3D*** flux model.
- Future possibilities for this analysis:
  - Improve selection, statistics and systematics.
  - 3-ν oscillation studies might be performed with enhanced shower reconstruction (need better direction and energy)
- Many thanks to the Cambridge group for use of ntuples, and overwhelming analysis support.

Backup Slides

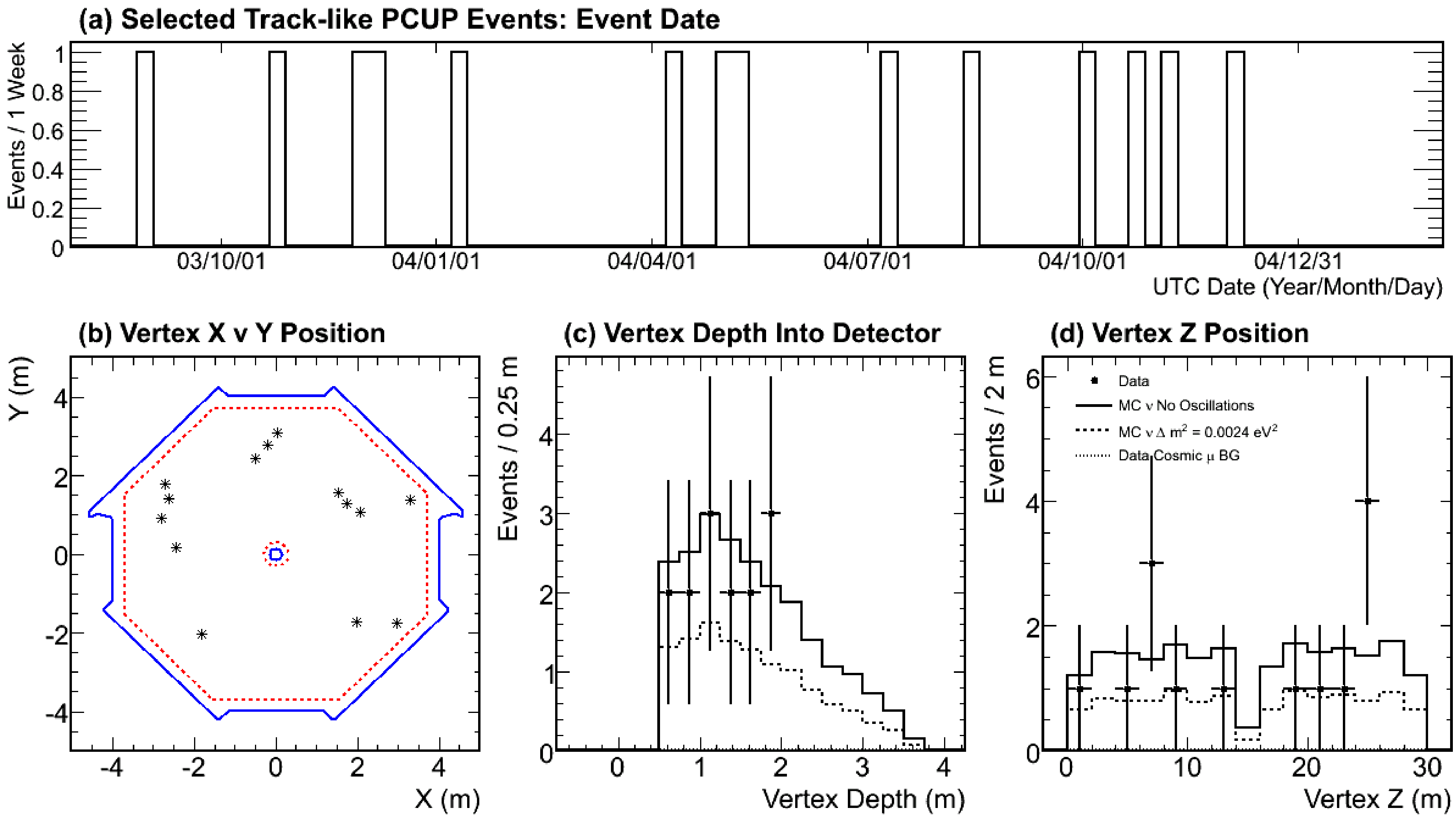
Projected Double Ratio Sensitivity

Project the double ratio and compare to SK

R = (0.63 ± 0.03 ± 0.05) for 46 kton-yr



Selected PCUP Track Events



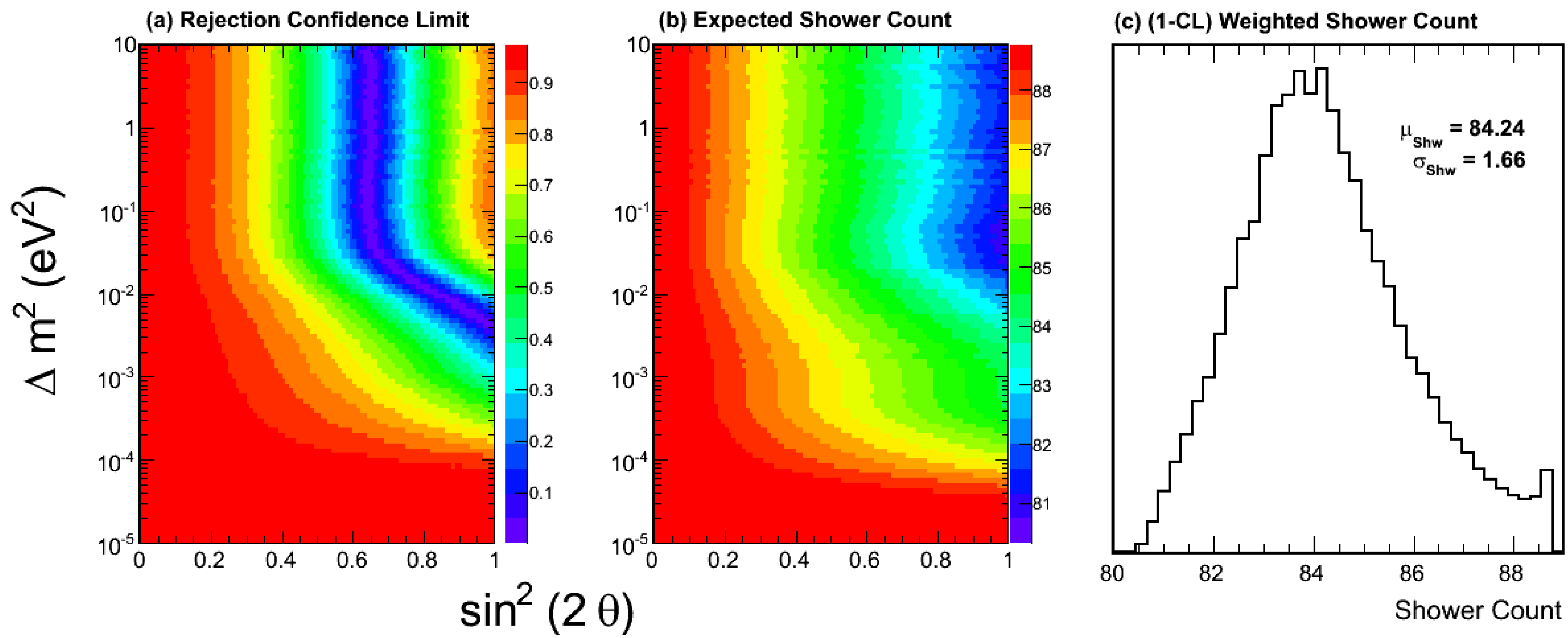
Frequentist Double Ratio Fit

- An oscillation hypothesis (null or otherwise) posits an expected double ratio
- The expected double ratio is fluctuated to estimate the confidence limit for rejecting the measured double ratio.
- Found expected shower count for each oscillation hypothesis
- Weight expected shower event count by (1- rejection CL).
- The distribution of (1-CL) weighted shower count is centered at the shower count to use, and the width is a systematic error due to oscillation uncertainty

DR Oscillation Fit + Normalize

Find range of confidence limits from DR frequentist fit

Apply the range of CL values to shower count



Flux Scale
Measurement and Systematics

Obtain Flux Scale (S_ν) from expected and observed shower counts.

$$S_\nu = Obs_{shw} / Exp_{shw}$$

Investigate the following systematic variances:

1. Tracking Energy Cutoff: 100keV vs.10keV
2. Quasi-Elastic cross-section: ±10%
3. Neutral-Current cross-section: ±25%
4. Neutron Flux Normalization: ±20%
5. Oscillation (1-CL) Weight Shower Count RMS

Flux Scale Method #1 Result

	$\Delta\ E_{Shw}$(%)	$\Delta\ S_{\nu}$(%)
10keV Cutoff	+4.86	-5.01
NC ±25%	±4.49	**-(**±5.19)
QE ±10%	±2.36	**-(**±2.54)
Neutron ±20%	±0.520	**-(**±0.556)
Osc (1-CL) Weight	1.91	2.12

Cumulative Systematic Error = 9.03%

$S_{\nu} = 1.06 \pm 0.12(\text{stat.}) \pm 0.09(\text{syst.})$

Flux Scale Method Comparison

- Double Ratio / Shower Count Method

  $S_\nu = 1.06 \pm 0.12(\text{stat.}) \pm 0.09(\text{syst.})$

  Statistically Consistent with S_ν=1.0 to 58.1%

  Stat + Syst Consistent with S_ν=1.0 to 66.2%

- Likelihood Track & Shower Count Method

  $S_\nu = 1.07 \pm 0.12(\text{stat.}) \pm 0.09(\text{syst.})$

  Consistent with first method.

Alternate Flux Measurements

- Soudan2 measures of Battistoni S_{atm} to be:

$$S_{atm} = 1.02 \pm 0.07 \text{ (with-osc)}$$

- Compared to the MINOS measurement:

$$S_{atm} = 1.22 \pm 0.12 \pm 0.09 \text{ (with-osc)}$$

- Soudan2 used GHEISHA to model hadronization, while the MINOS simulations have uses GCALOR due to the CALDET results. If the MINOS flux measurement is performed again with GHEISHA hadron modeling, the flux scale to the Barr model is:

$$S_{atm} = 0.98 \pm 0.12 \pm 0.09 \text{ (with-osc)}$$

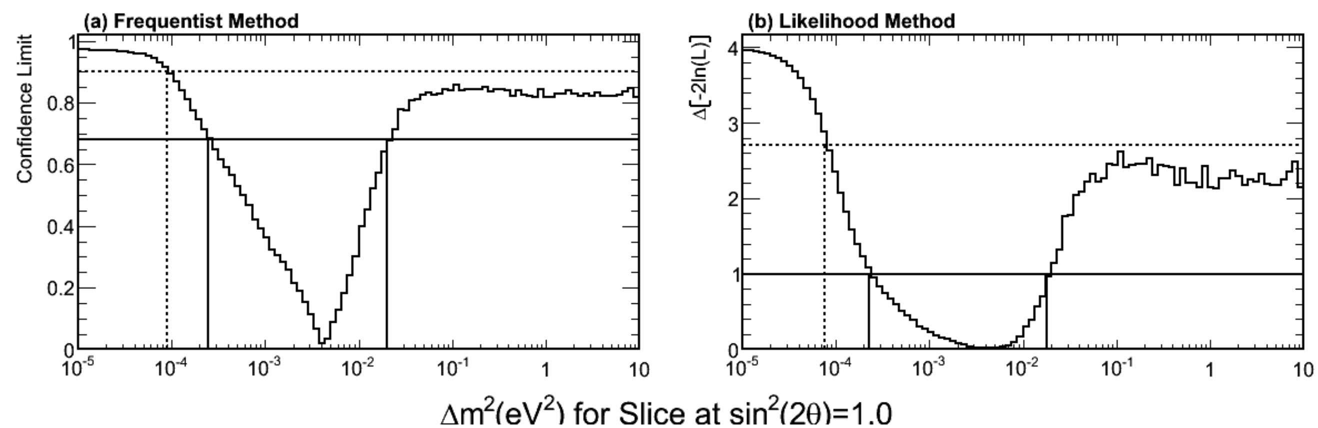
- Which may compare to the flux measurement from Soudan2 of:

$$S_{atm} = 0.91 \pm 0.07 \text{ (with-osc)}$$

Comparison of Oscillation Slices

- Take 1D Slices from 2D Osc grid and compare.
- Frequentist fit deals with 1 constraint and 2 parameters.
- Likelihood fit deals with 2 constraints and 3 parameters.
- Both fits are under-constrained, but differ in shape.
- 68% CL in red boxes, compare nicely between methods.

$2.43 \times 10^{-4}\ eV^2 < \Delta m^2 < 2.02 \times 10^{-2}\ eV^2$	$2.28 \times 10^{-4}\ eV^2 < \Delta m^2 < 1.78 \times 10^{-2}\ eV^2$



$\sin^2(2\theta) > 0.611$	$\sin^2(2\theta) > 0.592$